THE FIXED GLACIAL ANTICYCLONE COMPARED TO THE MIGRATING ANTICYCLONE.

By WILLIAM HERBERT HOBBS.

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The discussion upon the "General Air Circulation over the Antarctic" contained in Dr. Simpson's final report upon the meteorological observations made in connection with Captain Scott's last expedition,[1] is devoted especially to my theory of the glacial anticyclone and the opposite conception of the glacial cyclone as set forth by Meinardus, the meteorologist of the German South-Pole Expedition. Simpson's summing up of his conclusions is, however, a trifle difficult to evaluate, for he says:

> "On considering the whole of Hobbs' paper one cannot help feeling that in spite of his failing to explain the origin of the precipitation and the mechanism of blizzards he has made out a very strong case for the existence of an anticyclone over all extensive masses of inland ice and over the Antarctic in particular. Therefore one would be inclined to agree with the generally accepted idea that there is an intense anticyclone concentric with the Pole and covering the whole of the Antarctic Continent.
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> "On the other hand, however, Meinardus in his discussion of the results of the Gauss Expedition attacks the theory of the Antarctic anticyclone with great vigour and one must admit with most convincing success. We will therefore now examine the problem from Meinardus' point of view."

From these paragraphs one is unable to decide whether Dr. Simpson favors the one or the other theory. The following citations from his monograph will indicate that he has failed to grasp the fundamental physical fact which is the *raison d'être* of the anticyclone, namely, the domed surface of the continental glacier:

> "Hobbs . . . contends that an anticyclone exists over every extensive snow-covered land and takes the Antarctic and Greenland as the two most

[1] George C. Simpson, D.Sc., F.R.S., Meteorology, British Antarctic Expedition 1910–1913, Vol. 1, discussion (pp. 326, pls. 5) and Vol. 2, Weather Maps, Calcutta, 1919.

pronounced examples. To the anticyclones which owe their origin to a snow-covered land Hobbs has given the name 'glacial anticyclone' and he has worked out at considerable length the meteorological features of such anticyclones" (page 248).

"In my opinion . . . the descending air in the anticyclones is very poor in vapour." (Citation from Meinardus on page 249.)

"One must agree with Meinardus in this matter and there can be little doubt that Hobbs has left unsolved what we shall see in the next section is the greatest problem of the Antarctic anticyclone, namely, the origin of the precipitation within the anticyclone."

On page 250 of his report several statements are made by Dr. Simpson in summarizing my views (such, for example, as that the air moves inward *along the surface* to replace the surface outflow of air) which are without warrant and in common with the entire chapter reveal a very careless reading. I have therefore no recourse but to restate some of the more essential elements in my conception of the glacial anticyclone and to call attention to the several papers in which I have dealt with the subject.[2] Among later ones I would note especially a paper in the *Proceedings* of this society.[3]

In all my writings upon the glacial anticyclone I have been at much pains to explain that the domed surface of the ice is essential to the development both of the anticyclone and of the alternating calms and blizzards which record its strophic action. In my "Characteristics of Existing Glaciers" it is stated (p. 149): "It is due to the peculiar shield-like form of this ice-mass that the heavier cooled bottom layer (of air) is able to slide off radially as would a film of oil from a model of similar form. The centrifugal nature of this

[2] "The Ice Masses on and about the Antarctic Continent," *Zeitsch. f. Gletscherk,* Vol. V., 1910, pp. 107–20. "Characteristics of the Inland-ice of the Arctic Regions," *Proc. Am. Philos. Soc.,* Vol. XLIX., 1910, pp. 96–109. "Characteristics of Existing Glaciers" (Macmillan, 1911), Chaps. IX. and XVI. and Afterword. "The Pleistocene Glaciation of North America Viewed in the Light of our Knowledge of Existing Continental Glaciers," *Bull. Am. Geogr. Soc., Vol.* XLIII., 1911, pp. 641–59. "Earth Features and their Meaning" (Macmillan, 1912), pp. 283–86. "The Ferrel Doctrine of Polar Calms and its Disproof in Recent Observations," *Proc. Second Pan-American Scientific Congress,* Vol. II., Sec. II., Washington, 1917, pp. 179–89. "The Mechanics of the Glacial Anticyclone Illustrated by Experiment," *Nature,* July 22, 1920.

[3] "The Rôle of the Glacial Anticyclone in the Air Circulation of the Globe," *Proc. Am. Phil. Soc.,* Vol. 54, 1915, pp. 185–225.

motion tends to produce a vacuum above the central area of the ice-mass, and the air must be drawn down from the upper layers of the atmosphere in order to supply the void. It is here that is located the 'eye' of the anticyclone." Again (p. 266): "This anticyclonic circulation of the air is not determined in any sense by latitudes but is the consequence of air refrigeration through contact with the elevated snow-ice dome, thus causing air to slide off in all directions along the steepest gradients."

In my monograph published in the *Proceedings* of this society it is stated (Vol. 54, p. 188): "It is because the inland-ice masses have a domed surface that they permit the air which is cooled by contact to flow outward centrifugally, and so develop at an ever-accelerating rate a vortex of exceptional strength."

Despite the statements of Meinardus that the descending air within the anticyclone would be very poor in vapor, a statement which is approved by Simpson, we now know from the records of several Polar expeditions that within the eye of the glacial anticyclone there is found an area of calm with shifting light, variable winds and excessively high humidity which results in mist or fog or even showers of ice needles, whereas all about are outwardly directed air currents associated with relative low humidity.

From the Antarctic glacier we have the record of Amundsen made in the vicinity of the southern pole and that of Captain Robert Scott, who entered the same region about a month later. From the Greenland glacier we have the scientific reports of two professional and highly experienced meteorologists, de Quervain and Wegener, that of the former from about the median line of the ice-dome near latitude 68° N., and that of the latter from near the very center.

Captain Amundsen entered the central area of the Antarctic ice-dome near the 88th southern parallel, finding there what he believed to be a region of permanent calm or of light winds and of generally clear weather. The snow surface was smooth with no drifts. For a fortnight the sky was clear except on two days when there were snow flurries. Insolation was so intense that perspiration poured from the bodies of the men even when most of their clothing had been removed.

A month later Captain Scott entered the same general region and remained within it for about three weeks to report generally similar conditions. After passing the parallel of 87½° scarcely a day passed that he did not jot down in his diary the observation of variable light winds and of a soft snow surface. He appeared to be puzzled by the clouds "which don't seem to come from anywhere, form and disperse without reason." . . . "Coming and going overhead all day, drifting from the southeast and constantly altering shape, snow crystals falling all the time." Again and again he refers to the dampness and chill of the air and that when the thermometer was examined all were surprised that it recorded so high a temperature.

In Greenland de Quervain found the air over the ice within the central area moved by light variable winds and highly charged with mosture, the mist hiding members of the party at only moderate distances and the beards, caps, chins, etc., frozen into a solid mass of ice. In their report on the Swiss Greenland Expedition, de Quervain and Mercanton,[4] after giving in tabular form the data for humidity above the inland-ice along the route of the expedition, sum up as follows:

> We find, therefore, a quite high average relative humidity, 82 per cent. as well for the whole distance as for the central region, and a quite small daily variation of the relative humidity: this varies on the average for the entire time between the values of 88 per cent. and 77 per cent.; for the central zone the variation is somewhat greater, namely, between about 92 per cent. and 73 per cent. Near the border of the ice the relative humidity is less by about 5 per cent. (p. 136).

Koch and Wegener encountered farther north when crossing the central area of the ice-dome a region of atmospheric calm with much mist, which in the morning was so dense as to obscure the sun. Clothing was constantly wet and could be dried only with the greatest difficulty.

The most striking departures of ice-dome anticyclones from the ordinary travelling anticyclones are: (1) the fixed, as opposed to the migrating, position of the air whirl; (2) the location of this whirl

[4] Prof. Dr. Alfred de Quervain and Prof. Dr. P. L. Mercanton, Ergebnisse der Schweitzerischen Grönland Expedition, 1912–1913, *Denkschr. d. schweiz., Naturf. Gesell.*, vol. 53, 1920, pp. 402, pls. 4.

above a glacier of domed surface; (3) the pronounced strophic character of the circulation (calms alternating with blizzards), and (4) the notably different distribution of humidity. These attributes being all either connected directly with or depending upon the form and the location of the continental glacier, the expression *glacial anticyclone* adequately expresses both the resemblances to and the differences from the common type of migrating anticyclone.

Dr. Simpson has raised the point that the snow surface must during the summer season be warmer than the air above it, and in support he cites the effect of insolation upon snow *of the ice-barrier.* Over the glacier outlets such as the Beardmore, within which at the conclusion of a blizzard the foehn effect is enormously intensified; over the flat central areas of the ice dome; and, in Greenland, over the western marginal zone extending inwards some tens of miles, within which during the calms of the anticyclonic stroph the incoming whirls from the westward invade the ice-dome and scatter dust over its surface, similar effects have been observed. Over the vast area of the continental glaciers, however, and especially upon the slopes which induce the circulation, such effects have not, so far as I am aware, been recorded; and it is in point that during the summer season practically all our data have been gathered. From widely separated regions, on Greenland and over the Antarctic alike, we now possess a wealth of amazingly consistent testimony that, except for the brief interval at the conclusion of a blizzard when the anticyclone literally "turns itself inside out" and becomes momentarily a cyclone, the wind blows *down slope* though deviated to accord with the deflection from earth rotation (see *Proc. Am. Phil. Soc.*, Vol. 54, 1915, pp. 193–203).

In the report recently issued by de Quervain and Mercanton is supplied this significant statement:

> According to the experiences on the crossing and from our knowledge of the distribution of air pressure at the time, we were compelled to remain under the impression, which any worker must gain from our meteorological tables, that the most strongly marked, highly regular connection exists between the summer wind conditions of the central Greenland inland-ice and its topography. On the west side of the gigantic ice-shield regular *south-east* winds varying from strong to tempestuous; on the east slope, likewise,

somewhat less strongly marked *northwest* winds. Strongly stated, it appears indeed as if the air was streaming out after the manner of a liquid from the interior down the inclined slopes toward both coasts, but turned 45° to the right through the action of earth rotation.

Such a determination, even for summer conditions, gives support to the assumption of very marked *inland-ice anticyclones* in the sense of the interesting demonstrations of W. Hobbs (in "The Existing Glaciers"). Our advance results have therefore given added value to these views.

Barrier-ice is as regards its areas wholly subordinate to inland-ice within the Antarctic, and, so far as is yet known, it is peripheral and contained within embayments, yet the stations where meteorological observations have been continuously made in the Antarctic have generally been located off the inland-ice, upon the barrier, and always within the zone marginal to the glacier where the control of local circulation falls periodically under the domination of the glacial anticyclone as it passes through its strophic changes. This fact was recognized by David for the winter station of the Shackleton Expedition. Framheim, where the station of Amundsen was located, is somewhat less under the domination of the anticyclone from the neighboring King Edward Land than are the British stations under that of South Victoria Land, but the evidence of frequent control is not lacking.

Upon the borders of the Greenland ice dome, where quite similar conditions exist, though generally without the presence of barrier-ice, account of the periodical overwhelming of local circulation by the glacial anticyclone has been taken by the meteorologists who have established stations there. Brand and Wegener in Northeast Greenland in positions where topography especially favored such studies, and for the express purpose of evaluating the degree of domination by anticyclonic conditions, established a second station (Pustervig) close to the margin of the inland-ice and some forty miles distant from the main meteorological station at Danmarks-Havn. As a consequence it was learned that "in spite of the short distance of only 60 km. from Danmarks-Havn . . . this influence is very noticeable."[5] Until meteorological stations can be established upon the inland ice our best knowledge of circulatory condi-

[5] W. Brand and A. Wegener, *Meddelelser øm Gronland,* Vol. 42, 1912, pp. 451–562.

tions over continental glaciers will be obtained through assembling the observations recorded in the journals of sledging parties, notably the wind direction, the orientation of sastrugi, temperature conditions, snow surface and humidity.

Dr. Simpson's discussion of the Antarctic blizzard suffers especially because in his evaluation of the available moisture content of the air over the Antarctic region he has taken account, not of the water content in all states of aggregation within the unit of space, but of that portion only which is uncongealed and therefore registered by the usual hygrometric apparatus. Adiabatic changes readily transform the ice needles of the cirri into moisture, which until again congealed or crystallized is duly registered upon the hygrometric record, and if the congealed material is not to be entered in the accounting the proper equating of available moisture before and after an adiabatic meteorological change will be impossible. This is obviously the reason why Dr. Simpson says of my theory of the glacial anticyclone that it fails "to explain the origin of the precipitation and the mechanism of blizzards," and "Hobbs has left unsolved . . . the greatest problem of the Antarctic anticyclone, namely, the origin of the precipitation within the anticyclone." As a matter of fact, in all my papers upon the subject this process of precipitation and its origin in the blizzard itself has been elaborated, *not as an additional feature of the anticyclone, but as a necessary inherent quality which can in no wise be omitted.*

The continental glacier in its evolution must be conceived to have developed from enlargement of an ice-cap which is nourished like the mountain glaciers by ascending moist air currents. Ice-cap glaciers exist today on Iceland, in Norway, and as isolated masses on the borders of continental glaciers. Though in form they resemble continental glaciers, they are: (1) much smaller, (2) they are nourished by a wholly different process, (3) they owe their existence to their location upon a pedestal-like base which is relatively flat and extends above the snow line of the region.

An interesting question arises, "At what stage of their development will this type of glacier take on the auto-circulation of a continental glacier and by reaching up draw down the ice needles of the

cirri for its nourishment?" When will it first make its own weather instead of taking that which is brought to it by travelling whirls? A partial answer seems to be afforded by two glaciers, the Vatnajökull of Iceland and the inland-ice of Northeast Land, Spitzbergen. Some years ago Dr. Thoroddsen, who of all scientists was best acquainted with the Vatnajökull, informed me that it possessed no auto-circulation but appeared to be entirely dominated by the vigorous cyclonic whirls which summer and winter are located over the sea to the southwestward. This mass of ice is roughly elliptical in shape with major and minor axes of about eighty and fifty miles respectively and has an area of 8,500 square km. Subsequent observations by other observers lead me, however, to hold this as perhaps doubtful. A larger ice mass which is more nearly circular and with corresponding axes of one hundred and eighty miles is the inland-ice over Northeast Land, Spitzbergen. The narrative of Baron Nordenskiöld, who crossed it in 1873, clearly reveals the evidence of anticyclonic conditions.

The great glacial anticyclones of Greenland and the Antarctic can hardly be considered apart from their important rôle as parts of the earth's planetary system of winds—they perform an important service in turning backward toward the tropics those high level currents which have passed the horse latitudes and have not yet been brought down to the surface, in doing which they remove the moisture which had been locked up in the ice needles of the cirri. They undoubtedly lend vigor to the entire circulatory system and thus accentuate the climatic zones. When in the Pleistocene age far greater continental glaciers lay over North America and Northern Europe, the climatic zones must have been still more strongly marked. There appears to be in this an explanation of the fact, now generally recognized,[6] that in the geologic past climatic barriers have prevented the poleward or equatorward migrations of sensitive organisms only during such geologic periods as were characterized by extensive glaciation and presumably by correspondingly strong

[6] See F. H. Knowlton, "Evolution of Geologic Climate," *Bull. Geol. Soc. Am.*, Vol. 30, 1919, pp. 499–566.

climatic zonation, as I pointed out in 1916.[7] We are living today in the waning hemicycle of one of these abnormal glacial periods, and as a consequence have reconstructed much of the past geologic history, not upon the standard or typical pattern of the earth, but upon a markedly abnormal, short-lived and seldom occurring set of conditions which happens to be the one in which we are living.

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[7] W. H. Hobbs, "The Ferrel Doctrine of Polar Calms and its Disproof in Recent Observations," *Proc. Second Pan-Am. Sci. Congress,* Washington, 1915–16, sec. 2, pp. 185–187.